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ELECTRON ACCELERATORS FOR RESEARCH AT THE FRONTIERS OF NUCLEAR PHYSICS

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ABSTRACT

Electron accelerators for the frontiers of nuclear physics must provide high duty factor (>80%) for coincidence measurements; few-hundred-MeV through few-GeV energy for work in the nucleonic, hadronic, and confinement regimes; energy resolution of $\sim 10^{-4}$; and high current ($\geq$100 μA). To fulfill these requirements new machines and upgrades of existing ones are being planned or constructed. Representative microtron-based facilities are the upgrade of MAMI at the University of Mainz (West Germany), the proposed two-stage cascaded microtron at the University of Illinois (U.S.A.), and the three-stage Troitsk "polytron" (USSR). Representative projects to add pulse stretcher rings to existing linacs are the upgrades at MIT-Bates (U.S.A.) and at NIKHEF-K (Netherlands). Recent advances in superconducting rf technology, especially in cavity design and fabrication, have made large superconducting cw linacs become feasible. Recirculating superconducting cw linacs are under construction at the University of Darmstadt (West Germany) and at CEBAF (U.S.A.), and a proposal is being developed at Saclay (France).

INTRODUCTION

At a conference celebrating 35 years of electron physics made possible by past generations of electron accelerators, it is timely to look toward the future to identify the electron beam parameters, accelerator technologies, and facilities needed to continue to advance the frontiers of physics. Here we perform this survey for nuclear physics, where electrons have served as precise probes of nuclear and nucleon structure. The information presented here is discussed in the context of a broadly based, future nuclear physics program that includes advanced accelerators providing high-energy heavy ion and hadronic probes to obtain essential insights into nuclear matter that cannot be obtained using electron machines.[1] These other accelerators are not discussed here.

Before describing future electron accelerators and their technologies, it is appropriate to consider briefly the physics issues that these machines will be built to address, and to see what beam requirements they set. In the past, electron scattering experiments have provided precise information about nuclear wave functions, excited states, charge densities, and magnetization densities. Increasingly fine energy

Table 1
Operating Electron Accelerators for Nuclear Physics

Machine	Location	Type	Energy (MeV)	Average Current (μA)	Duty Factor (%)
Illinois	Urbana, IL, USA	microtron	100	10	100
MAX	Lund, Sweden	microtron/PSR	100	30	≥90
Tohoku	Sendai, Japan	linac/PSR	150	3	90
*MAMI	Mainz, W. Germany	microtron	180	100	100
EROS	Saskatoon, Canada	linac	300	70	0.1
Frascati	Frascati, Italy	linac	400	80	1
MEA/NIKHEF-K	Amsterdam, Netherlands	linac	530	60	1
ALS	Saclay, France	linac	720	100	1
*Bates/MIT	Middleton, MA, USA	linac	850	100	1
*SLAC/NPAS	Palo Alto, CA, USA	linac	4000	15	0.03

*Polarized beam available

Table 2
Future Electron Accelerators for Nuclear Physics

Machine	Location	Type	Max. Energy (GeV)	Average Current (μA)	Duty Factor (%)	Status
Darmstadt	W. Germany	recirc SC linac	0.13	20	100	Under construction
Lebedev	Moscow, USSR	microtron	0.14	100	100	Under construction
NBS	Gaithersburg, MD, USA	racetrack microtron	0.20	200	100	Under construction
EROS	Saskatoon, Canada	linac/PSR	0.30	70	≥80	PSR under commissioning
Illinois	Urbana, IL, USA	cascaded microtron	0.45	100	100	Proposed
Update/NIKHEF	Amsterdam, Neth.	linac/PSR	0.7	40	≥80	Proposed
*MAMI	Mainz, W. Germany	cascaded microtron	0.84	100	100	Under construction
*Bates/MIT	Middleton, MA, USA	linac/PSR	1.0	100	≥85	PSR proposed
	Frascati, Italy	SC linac	~1.0	?	100	Under consideration
ADONE	Frascati, Italy	synchrotron	1.5	80	1-5	Internal target capability under construction (bremsstrahlung) proposed (scattering)
ALS-II	Saclay, France	recirc SC linac	1.5-2	100	100	Design in progress
*ELSA	Bonn, W. Germany	synchrotron/PSR synchrotron/booster	2.3 3.5	0.2 0.04	95 20	Construction nearly complete
*CEBAF	Newport News, VA, USA	recirc SC linac	4.0	200	100	FY 1987 start (?)
Lebedev	Troitsk, USSR	cascaded polytron	4.5	100-200	100	Proposed

*Polarized electrons available

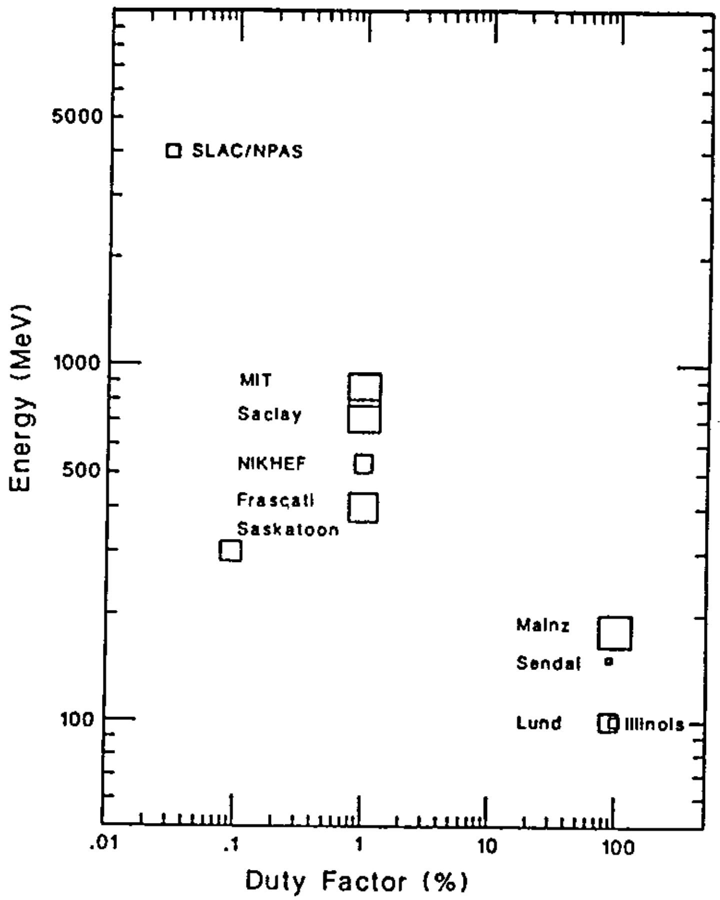

Figure 1. Electron accelerators now operating. The area of the box representing a given machine is proportional to the machine's current. (For reference, the Mainz box represents a current of 100 μA.)

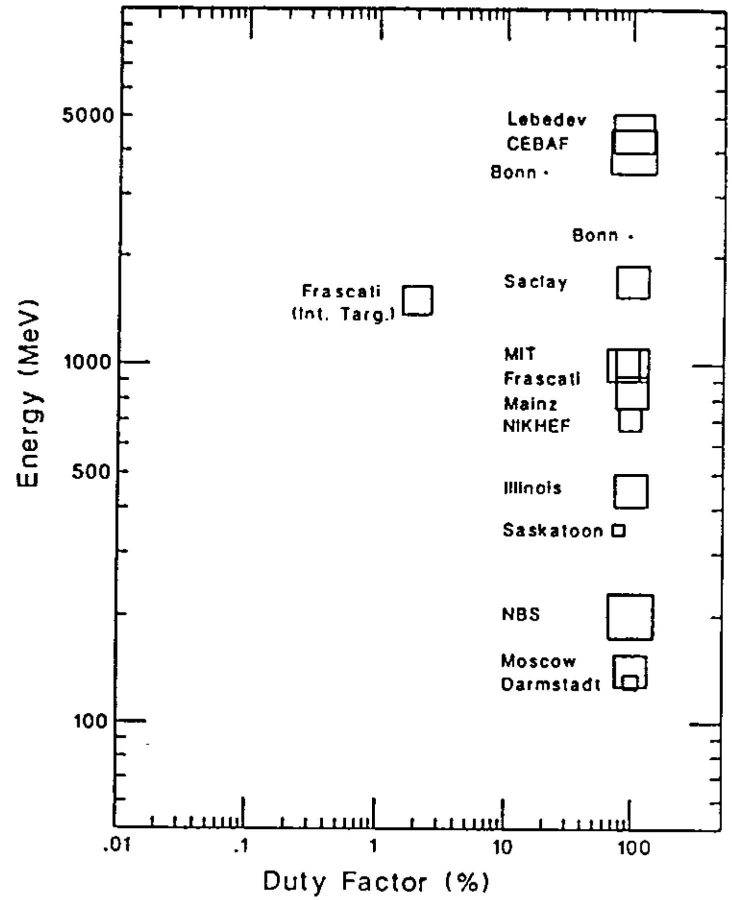

Figure 2. Future electron accelerators.

resolution achieved by existing electron accelerators has made it possible to isolate individual quantum states. However, coincidence measurements, in which the scattered electron and one or more nucleons or mesons it has knocked from the nucleus are studied in coincidence, provide more details about nuclear structure than can be obtained from inclusive scattering. This recent emphasis has resulted in a push for electron accelerators capable of delivering continuous beams, which greatly facilitate coincidence studies.

In parallel with the demand for more complete characterization of the scattering interaction has come an interest in even smaller subnuclear constituents. A particular focus is the transition between the nucleon-meson and the quark-gluon descriptions of nuclear matter. This interest is pushing the required electron energy higher -- to the few GeV range -- while unresolved issues related to nuclear structure on coarser scales will continue to be tackled.

Three major nuclear regimes, corresponding to different accelerator energy ranges, have been identified.[2]

1. Nucleonic: Spatial resolutions of a few fm, where the nucleus behaves as a collection of nucleons (electron momentum transfer up to a few hundred MeV/c).
2. Hadronic: Spatial resolution of the order of 1 fm, where the role of mesons and excited nucleon states is important (electron momentum transfer between a few hundred MeV/c and a few GeV/c).
3. Confinement: Spatial resolution less than 0.1 fm, where the details of nucleon structure, interactions between the nuclear medium and the nucleon, and quark confinement can be studied (electron momentum transfer above 1 GeV/c).

To explore these regimes requires some new and some upgraded electron accelerators to span the energy range between a few hundred MeV and several GeV. These accelerators will offer a combination of features: a high duty factor ($\gtrsim$80%), fine energy resolution ($\sim 10^{-4}$), ample beam current ($\gtrsim$100 μA), and excellent beam quality.

Accelerator technology has kept pace with these requirements. There are now three viable approaches for producing high duty factor or continuous wave (cw) electron beams: microtron, linac with pulse stretcher ring, and superconducting cw linac. A microtron provides high duty factor and excellent beam quality with high energy resolution, but is limited in its maximum energy. A room-temperature (normal conducting) linac with pulse stretcher ring (PSR) offers high energy, high current, high but modulated duty factor, and modest beam quality. A superconducting cw linac can provide high energy, high duty factor, excellent energy resolution, and high current.

In this paper, which updates the reviews by Herminghaus[3] and Flanz,[4] the capabilities of operating electron accelerators for nuclear physics are summarized, generic design issues associated with each accelerator approach are discussed, and the features of representative planned electron accelerators for nuclear physics are described.

OPERATING ELECTRON ACCELERATORS

Table 1 lists the major operating electron accelerators for nuclear physics. Figure 1 graphically compares these facilities in terms of energy, duty factor, and current. Existing machines provide either high energy or high duty factor, but not both. The six machines with high energy but very low duty factor are pulsed, room-temperature linacs. Of the four low-energy, high-duty-factor machines, Mainz and Illinois are microtrons, Lund is a microtron with PSR, and Sendai is a linac with PSR.

FUTURE ELECTRON ACCELERATORS

Several laboratories and universities have developed and proposed designs for electron accelerators to access one or more of the three main nuclear regimes: the nucleonic, hadronic, and confinement regimes. These machines are listed in Table 2. Their capabilities are presented graphically in Figure 2, which illustrates the uniform quest for high duty factor throughout the energy ranges of interest.

Four of the machines are to be microtrons: Illinois, NBS (National Bureau of Standards), the Mainz upgrade of MAMI (MAinz MIcrotron), and the Troitsk-Lebedev "polytron." Illinois is awaiting a funding decision, the Mainz upgrade is in progress, and a prototype first stage for Troitsk is under construction in Moscow. The NBS microtron was terminated in late 1986 as a nuclear physics project, and is being converted to a free electron laser (FEL) facility. NIKHEF-K in Holland, MIT-Bates, and EROS (Electron Ring of Saskatoon, Canada) have proposed pulse stretcher ring (PSR) additions to existing pulsed linacs. The PSR at EROS is nearly operational, while the other projects are awaiting final funding decisions. Of the four superconducting linacs, two are under construction (the Continuous Electron Beam Accelerator Facility (CEBAF) in Virginia and the University of Darmstadt in West Germany), one is being designed to replace the pulsed Accelerateur Lineare de Saclay (ALS) linac in France, and one is under consideration at Frascati, Italy. The low-duty-factor Frascati internal target experiment and the two low-current Bonn machines shown on the figure are synchrotrons.

Representative microtron, linac-PSR, and superconducting linac projects are discussed in the following sections, after a brief discussion of the characteristics and issues associated with each design approach.

Microtrons

A microtron[5] is an energy-efficient approach to producing energetic particle beams, because the accelerating structure is reused many (N) times. In a classical microtron, the accelerating structure consists of a single rf cavity placed in a uniform magnetic field (Figure 3).

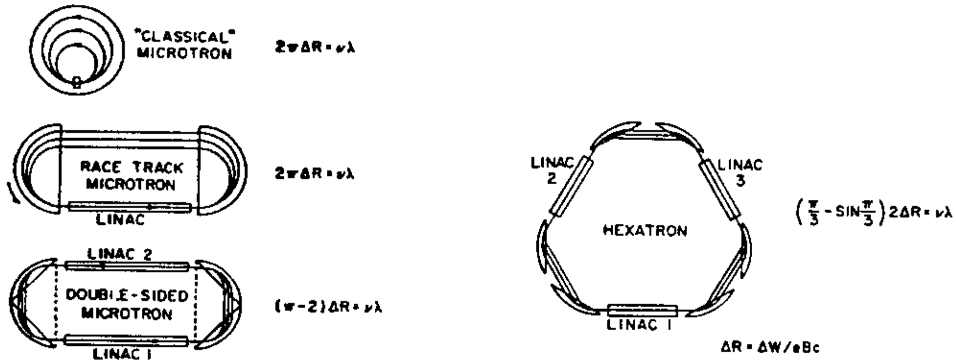

Figure 3. Variations on the microtron.[6]

On sequential recirculations the beam moves through circular orbits of increasing radius. The orbits share a common tangent at the cavity. The microtron resonance condition requires that the time difference between successive orbits be an integral multiple of the rf period to ensure that the beam reenters the cavity in phase on each pass. For fully relativistic particles, the path-length difference (ΔL) between successive orbits must be an integral multiple of the rf wavelength (λ).

$$\Delta L = n\lambda \qquad\qquad (n=1,\ 2,\ ..)$$

Usually n is less than 5 to optimize phase acceptance.

In a racetrack microtron, the magnetic field is split into two halves, which are separated and have a linac section placed between them (Figure 3). Particles trace elongated, racetrack-shaped orbits, which all pass through the linac. On successive recirculations the radius of the beam trajectory through the end magnets increases, thereby increasing the width of the racetrack orbit. The increased path length must still obey the resonance condition given above, and quite stringent requirements are placed on the field uniformity of the end magnets. The Illinois and Mainz accelerators are racetrack microtrons.

By splitting the end magnets and recombining the beams for acceleration through a second linac on the return path, a double-sided microtron can be built (Figure 3). Multisided polytrons with three or more linac segments separated by split "end" magnets have also been designed.[6,7] The Troitsk machine described below is an example.

The beam energy achieved by a microtron is $N \bullet \Delta E + E_{inj}$, where ΔE is the energy gain per pass and E_{inj} is the injection energy. Typically N is between 20 and 90. To achieve an energy higher than achievable by one microtron, present proposals call for cascaded machines, where the extracted beam from one microtron is injected into a second one (and possibly a third) for further acceleration. All three proposals discussed here are for cascaded microtrons.

Advantages of microtrons include energy efficiency, an ability to extract several beam energies simultaneously by extracting portions of the beam from different orbits, smooth (truly cw) macroscopic time structure, with microscopic time structure corresponding to the rf frequency, and excellent beam quality at low energies where quantum excitation is small. In addition, microtrons have intrinsic phase stability.

The major design issues for microtrons are accurate beam control and correction, beam breakup, and emittance growth due to synchrotron-radiation-induced quantum excitation. These issues are treated briefly below.

Accurate beam control and careful correction of errors in the beam transport system are required to maintain the appropriate phase between the rf accelerating voltage and the beam bunches and to maintain the position of the beam in the bore of the structure.

Because the total time that electrons spend in the microtron is extremely short compared with the time they would spend in a storage ring, instabilities characteristic of storage rings do not occur in microtrons. Only two types of beam instabilities tend to limit microtron currents.[8] The first, cumulative beam breakup, occurs when an electron bunch passes off center through the accelerating structure and excites transverse modes. These transverse fields deflect other electron bunches, which excite the modes further. The second instability, regenerative multipass breakup, occurs when the transverse modes excited by one electron bunch deflect the same bunch on its subsequent passes through the linac structure. These instabilities are not a problem, at present intensity levels, in microtrons with room-temperature accelerating structures, but appear to have limited the current of microtrons with superconducting accelerating structures.[9] Apparently the low Q's of the copper structures effectively damp the disruptive modes.

Above a few GeV, synchrotron radiation tends to increase the emittance of electron beams significantly. The emission of this radiation occurs in randomized energy quanta, so there is a spread in the radiated energy. This energy spread translates into growth in both the transverse and longitudinal emittances. At high energies, this quantum excitation determines the beam emittance. Thus, it is a major factor in choosing the accelerating-structure aperture, and may limit the maximum energy achievable with microtrons to a few GeV.

The Mainz microtron upgrade, the Illinois proposal, and the Troitsk polytron are described below. All are cascaded microtrons.

Mainz (MAMI). The final stage of a three-stage racetrack microtron is under construction at the Institute for Nuclear Physics of the University of Mainz, West Germany (Figure 4). When completed, MAMI-B will produce an 840-MeV, 100%-duty-factor, 100-μA beam with 10^{-4} energy resolution.[10,11] Its experimental program will focus on studies of hadronic degrees of freedom.

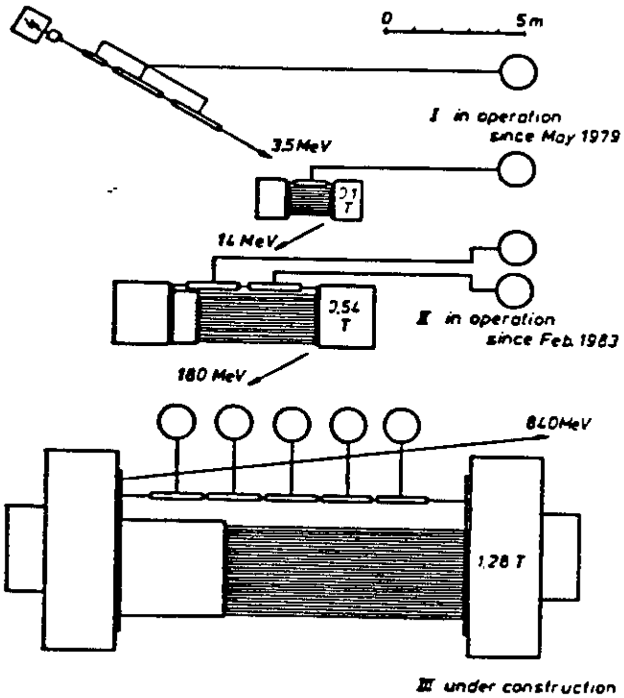

Figure 4. MAMI.

In the completed facility, electrons from a 3.5-MeV linac will be injected into Stage 1. After 18 passes through one 0.6-MeV, 80-cm section of copper accelerating structure for an output energy of 14 MeV, the beam will be sent to Stage 2, where 51 passes through a pair of 1.78-m accelerating sections providing 3.25 MeV per pass will lead to an output energy of 180 MeV. In 88 traversals of the five-section, 7.5-MeV linac of Stage 3, the beam will attain 840 MeV. The MAMI-B project includes, in addition to the third-stage 840-MeV racetrack microtron, a new injector linac to replace the present Van de Graaff. A polarized source is planned, along with a beam splitter to produce three beams simultaneously. A new experimental hall to house three spectrometers may be added later.

The MAMI facility was originally conceived in 1974. The first stage became operational in 1979, and was the first room-temperature racetrack cw microtron. The second stage was commissioned in 1983. By January 1987, the accelerator hall for Stage 3 was completed, and the first end magnet had been received. The first beam from Stage 3 is scheduled for early 1989.

Illinois. The Nuclear Physics Laboratory of the University of Illinois has proposed construction of a 100%-duty-factor, 100-μA two-stage cascaded microtron (Figure 5) for experiments in the energy range from 80 to 450 MeV.[9] A beam energy spread of 10^{-4} is expected. This machine is designed to perform high-resolution studies of nucleonic and mesonic degrees of freedom.

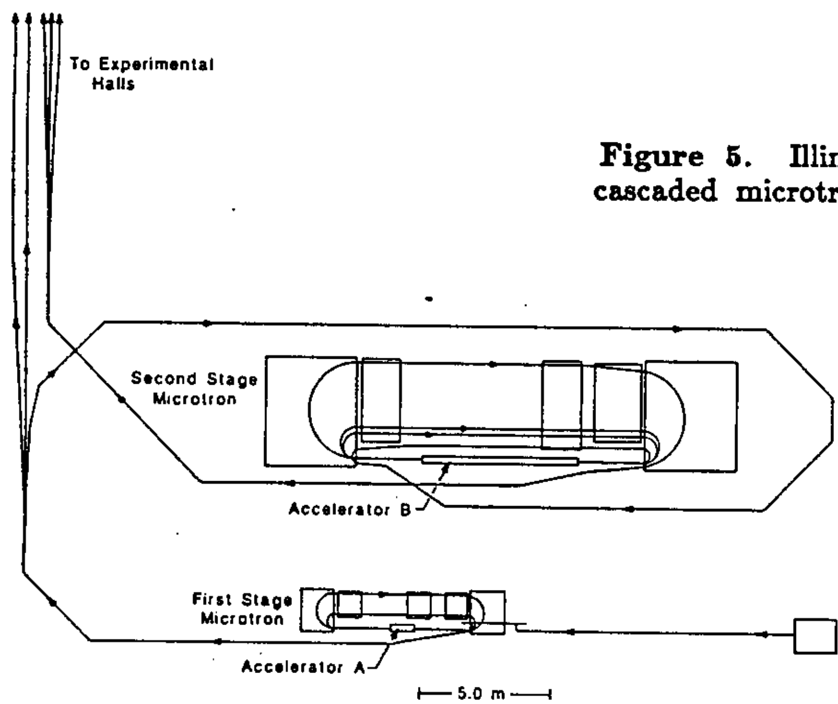

Figure 5. Illinois cascaded microtron.

Electrons injected into the first stage at 4.5 MeV will traverse a 1-m, 1.45-MeV linac 29 times for an output energy of 46.7 MeV, and then attain a final energy between 82 and 456 MeV (variable in 11.7-MeV steps) in 6 to 70 passes through the 6-m, 5.84-MeV linac of the second stage. Up to three simultaneous beams at the final energy or at a combination of the final energy and the first-stage output energy can be delivered to experimenters through the use of a subharmonic chopper in the injector and rf separators between Stages 1 and 2 and at the second-stage output. For full-beam-power experiments, the 100-μA beam is available by switching off the separator. Capability for parasitic tagged photon beams is under consideration. A capability for polarized beams is not included, but could be added, and design studies are underway.

Both the proposal and the ensuing research and development have been undertaken in the context of Illinois' experience building and operating microtrons. In 1972, MUSL-1 (Microtron Using a Superconducting Linac) at Illinois became the first operating cw racetrack microtron. A second racetrack microtron, MUSL-2, now provides 10-μA cw beams at energies up to 100 MeV. The proposal for a cascaded microtron has been favorably reviewed. Working prototypes of key components are in hand, funding for construction has been requested from the U.S. National Science Foundation, and a decision is pending for a construction start in FY 1988.

Troitsk "Polytron". Whereas the microtrons discussed above will operate below 1 GeV, where emittance growth due to synchrotron radiation is not severe, accelerator designers in the Soviet Union have proposed a 4.5-GeV cascaded "polytron" (Figure 6) for the Lebedev Physics Institute at Troitsk.[7] The physics goals include exploring the transition region and understanding quark confinement. The design calls for 100% duty factor, 300-μA current, and an energy resolution of 10^{-4}. The design has three stages: 7-MeV injection for 200-MeV output after 16 passes through the first-stage racetrack microtron, attainment of 1 GeV in 16 passes through the second-stage "quadrutron," and final energy of 4.5 GeV after 10 passes through the third-stage "octutron." The racetrack microtron includes one 8.5-m linac providing 12 MeV of acceleration. The quadrutron has two parallel 20-m linacs of 25 MeV each, and the octutron has four 77-m-long linacs providing 90 MeV each. The machine was proposed in 1984. A prototype first-stage microtron--140 MeV, 100 μA--is under construction in Moscow.

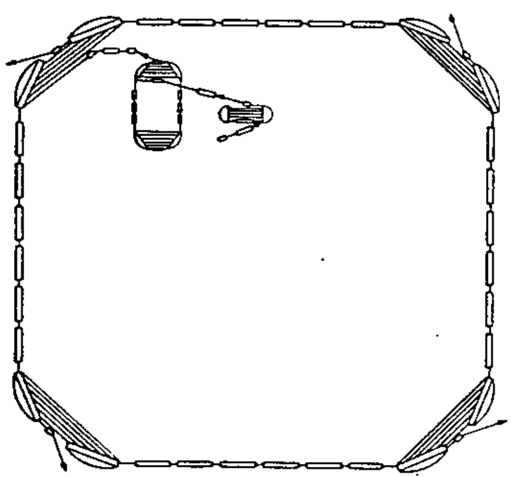

Figure 6. Troitsk "polytron."

Linacs with Pulse Stretcher Rings

Room-temperature linacs are capable of producing cw electron beams if they are operated at a low (~1 MV/m) accelerating gradient. However, both the capital cost of the required length of structure and the electric power consumption to achieve high electron energies are prohibitive. Therefore, room-temperature linacs are operated in a pulsed mode, with heavy beam loading during the pulse. Typical pulse durations are of the order of 1 to 50 μs, and the pulse rates may be of the order of 100 to 1000 Hz. The duty factors thus range from ~0.1% to a few percent. To reduce capital and operating costs, one recirculation through the linac can be employed.

By injecting the linac pulse into a ring, and extracting the beam slowly and uniformly during the interval between pulses, the duty factor from a pulsed linac can be increased to above 80%. Such a ring is known as a pulse stretcher ring (PSR) (Figure 7).[12]

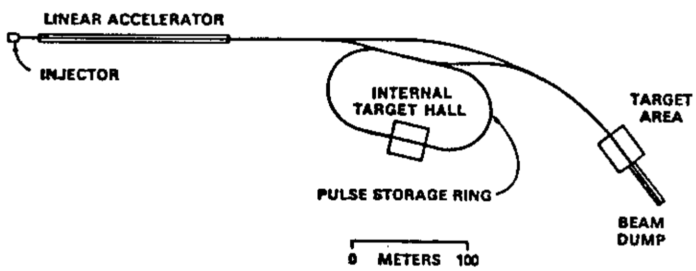

Figure 7. Generic linac-PSR.

Beam injection into the PSR is typically accomplished by single-turn, two-turn, or three-turn injection, such that the head of the electron pulse travels exactly once, twice, or three times around the ring before the tail enters. Resonant extraction is used to extract the beam during the few hundred to few thousand orbits traversed before the ring is empty and readied for the next pulse. This cycle is a rather fast "slow resonant extraction" mode, when compared with the slow extraction over a million turns from a proton synchrotron.

Pulse stretcher rings provide a cost-effective approach to producing high-duty-factor beams from existing pulsed linacs. In addition, they provide the capability for internal target experiments within the PSR. Beam quality, in terms of both emittance and energy spread, is degraded compared with that of an intrinsically cw machine, due to the high peak current in the linac. Continuous beams at only one energy can be delivered at any time, and to change energies requires resetting and retuning the PSR.

The major design issues for linac/PSR facilities are instabilities in the linac and PSR, and smooth extraction from the PSR. In addition, rf power requirements for the linac may place difficult demands on the rf system and components.

Instabilities in both the linac and PSR must be controlled. In the linac, peak currents are sufficiently high that cumulative beam breakup is the primary concern; multipass beam breakup also must be considered if recirculation is used. In the PSR, the beam must avoid the numerous instabilities that plague high-current electron storage rings.[13] However, the residence time is sufficiently short that many of these instabilities lack the time to develop and are not a problem. Unfortunately, for the same reason, essentially no beam conditioning will occur, because the time constant for beam damping significantly exceeds the residence time.

Of major importance is precise control and careful design of the extraction process. To ensure that the extracted beam is uniform over time, careful attention must be paid to the resonant extraction system and its feedback control. Modulations in the intensity of the extracted beam reduce its duty factor.

The proposals by MIT-Bates and by NIKHEF-K in Holland to add PSR's to their operating pulsed linacs are described below. PSR construction at EROS in Saskatoon, Canada has been completed; commissioning is expected to continue through mid-1987, at which time its 100- to 300-MeV, 70-μA beam at 80% duty factor will be available for experiments.[14]

<u>MIT-Bates Upgrade</u>. Presently operating at MIT-Bates is an 850-MeV, 1%-duty-factor, recirculating, pulsed linac. The key elements in the proposed upgrade of this machine are a PSR, an internal target hall, and a recirculator extension.[15] Main beam parameters of the proposed design are 300-1000 MeV energy, ~85% duty factor, 100-μA current, and energy resolution of 4×10^{-4}. A polarized injector is being commissioned.

Figure 8 shows the general layout of the upgrade. The PSR operates on one- or two-turn injection. The internal target hall intersecting the PSR allows use of the 40-80 mA circulating current for experiments with gaseous or very thin targets. An energy compression system has been incorporated to reduce the energy spread prior to injection into the PSR. The recirculator extension improves the machine's performance at high energy by allowing a head-to-tail recirculation of a beam pulse suitable for two-turn injection. Besides providing for 100-μA beams at energies above 500 MeV, the extension improves beam quality and operational reliability.

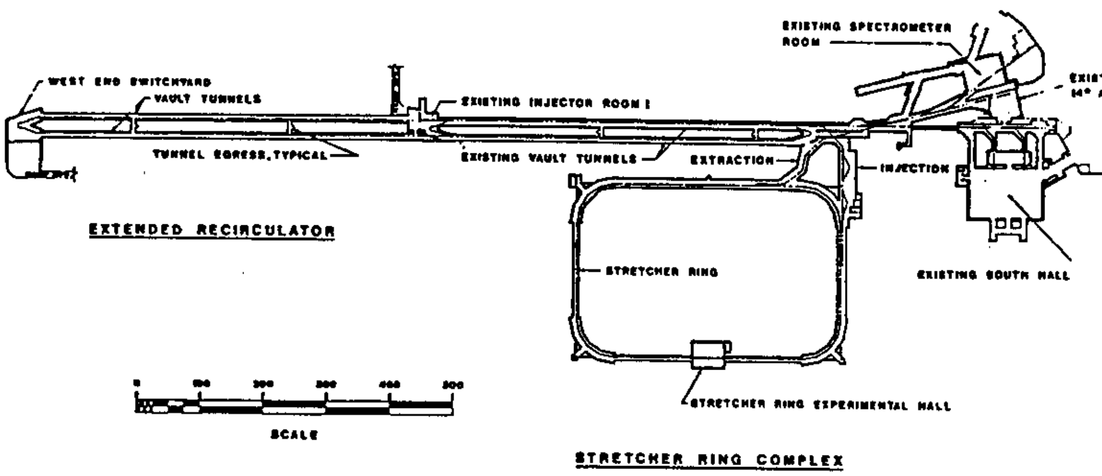

Figure 8. MIT-Bates linac-PSR.

The machine, as upgraded, would continue MIT's tradition of leadership on high-resolution studies of hadronic degrees of freedom in nuclei. It has been proposed for funding to the U.S. Department of Energy and endorsed by the U.S. Nuclear Science Advisory Committee. Preconstruction R&D is underway, and a decision on construction is pending.

<u>NIKHEF-K</u>. An upgrade, called Update, has been proposed for the presently operating pulsed 500-MeV, 1%-duty-factor electron linac at NIKHEF-K in Amsterdam[16] (Figure 9). Plans are for a PSR to be added, and for its injection energy--the output energy of the present linac--to be raised to 700 MeV by upgrading four or five of the linac's twelve klystrons. The PSR will use three-turn injection. To fill the PSR, the linac will operate with a shorter pulse length than at present, and at a duty factor of 0.1%. Since the linac will accelerate a higher peak current than at present, an energy compressor will be installed between the linac and the PSR to reduce the energy spread for injection into the PSR. The new performance parameters will be 15-700 MeV energy, 40 μA average current, >80% duty factor, and 5×10^{-4} energy resolution. During the fall of 1986, the proposal was reviewed favorably, and a funding decision is pending by the Dutch government.

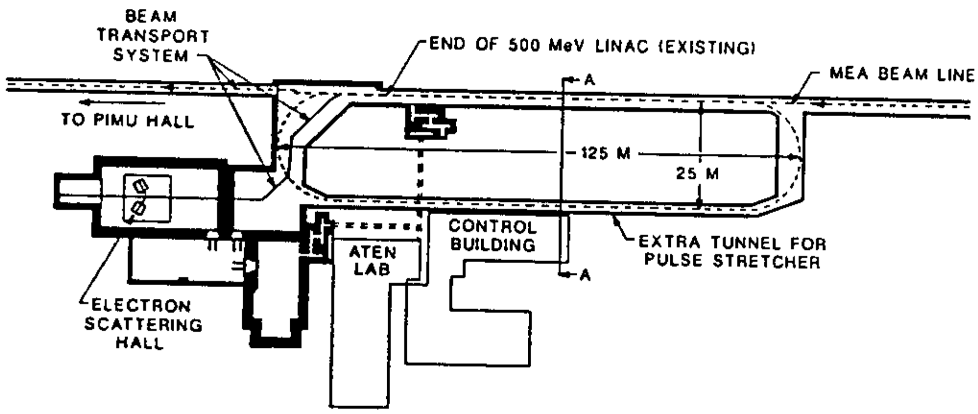

Figure 9. NIKHEF-K linac-PSR.

Superconducting CW Linacs

Superconducting linac structures have a significantly higher Q and therefore a significantly higher shunt impedance than room-temperature structures. This gain of a factor of 10^6 translates into a comparable decrease in power loss in the structure. Over 99% of the rf power goes into the beam, and only a small amount heats the walls.

To achieve this high rf efficiency, the accelerating structure must be kept superconducting. A liquid helium refrigerator is necessary to maintain these temperatures and to remove the rf-generated heat. Such a refrigerator operates at an efficiency of around 0.1%. Thus to remove 1 kW of heat requires around 1 MW of AC power for the refrigerator. Whereas it takes a few hundred MW of rf power to produce a 1-MW beam from a room-temperature cw linac, it takes only a few MW, mostly for cryogenics, to drive a comparable superconducting cw linac. Temperature optimization involves trading off cavity performance and heat loss (which are better at lower temperatures), with the complexity and cost of the cryogenic system (which are better at higher temperatures). Operating temperatures for existing and proposed superconducting accelerators are in the range 1.8 K to 4.5 K, depending on the rf frequency and the cavity material.

The most straightforward cw accelerator is a single linac, which the beam traverses only once. With an accelerating gradient of 5 MV/m, the capital cost of the length of a structure required to achieve high energies makes it economically unattractive. A more cost-effective solution is obtained by passing the beam a few times through a shorter linac structure. This concept is similar to that used for the microtron; however

1. fewer recirculations are used,
2. the recirculation paths are all separate and employ strong-focusing lattices to control beam quality,
3. phase stability is not intrinsic, and

4. the energy gain per pass can be arbitrarily large.

By appropriate selection of the field strengths of the bend magnets in each recirculation path, the lengths of all paths can be made essentially equal, and the recirculation beam lines can be stacked vertically in one tunnel.

In a recirculating linac the path of a single electron bunch from injector to experimental area comprises several (N) acceleration cycles, each of which is as follows:

1. injection into the linac,
2. acceleration by the linac,
3. "spreading" to the proper beam line for recirculation, and
4. transport through the recirculator to a recombiner for reinjection into the linac.

At any time, there are electrons at N energies passing simultaneously through the linac. Since all the particles are fully relativistic there is negligible phase slip during a pass. On the final cycle, this sequence is interrupted for extraction at step 3 where the beam, after spreading, enters an extraction beam line. Extraction elements can be placed in each of the recirculation arc beam lines to allow extraction on any of the preceding cycles as well. Such an arrangement makes possible the simultaneous delivery of beams at different but correlated energies.

The key issues for a recirculating, superconducting cw linac are beam stability, beam quality, and cavity design and performance.

In a recirculating linac, as in a microtron, the beam current is limited by multipass regenerative beam breakup.[17, 18] Since the Q of superconducting cavities is so high, this problem is potentially more serious than it is for room-temperature linacs. Its solution lies in designing the accelerating cavities to damp the offending transverse modes to acceptable levels.

The second issue is the problem of conserving the emittance and momentum spread. In a recirculating linac two factors can degrade the beam: synchrotron radiation during bending in the recirculation arcs, and possible phase mismatch of the electron beams upon reinjection into the linac segments. Beam quality can be maintained and reinjection mismatches avoided through proper design of the lattices in the recirculation arc beam lines. Suitable lattices are similar to those employed in low-emittance storage rings.[19] These lattices control beam path length and provide isochronicity, achromaticity, and careful correction of chromatic effects to facilitate reinjection after each recirculation. Strong focusing minimizes emittance growth caused by quantum excitation due to synchrotron radiation.

Superconducting cavity design and performance have been the subject of considerable R&D since the 1960s when a superconducting cw electron linac was first proposed.[20, 21] Major R&D efforts have been underway at Stanford, Karlsruhe, Cornell, CERN, DESY, Wuppertal, Orsay, and KEK. The goal has been to achieve high Q's and high gradients, which requires controlling surface defects and cleanliness, multipacting, and field emission. In addition, the transverse modes must be suppressed to achieve beam stability. Until recently, achieved gradients were limited to about 3 MV/m. Now gradients of 5 to 7 MV/m with Q's in excess of 10^9 are achieved routinely, at laboratories and by industry (Table 3).[22] These gradients already significantly exceed the cw gradients (~1 MV/m) feasible with copper cavities. Recent progress has been very rewarding, and there are firm plans now to employ these structures in several planned accelerators and major upgrades for nuclear and high energy physics.[23]

Table 3
Performance of $\beta=1$ Superconducting RF Cavities

Laboratory	CERN			KEK	DESY	Cornell	CEBAF**	Darmstadt/Wuppertal	
Accelerator	LEP II			TRISTAN	HERA	CESR	CEBAF	130 MeV	Recyclotron
Material	Nb	Nb	Nb/Cu	Nb	Nb	Nb	Nb	Nb	Nb_3Sn
Frequency (MHz)	350	500	500	500	1000	1500	1500	3000	3000
Operating Temperature (K)	4.2	4.2	4.2	4.2	4.2	1.8	2.0	1.8	4.2
Best Single-Cell Results									
E_A (MV/m)	10.8	13.0*	10.8	7.6*	5.5	22.8*	-	23.1*	7.2
Q at E_A ($\times 10^9$)	1.8	0.7	0.4	0.6	0.5	2.5	-	1.2	1.1
Best Multicell Results									
No. of Cells	4	5	4	3	9	5	5	5/20	5
E_A (MV/m)	7.5*	5.0	5	5.8	5.5	15.3*	12.0*	12.3/7.4	4
Q at E_A ($\times 10^9$)	2.2	0.7	0.8	0.6	0.5	2.2	2.4	3.5/1.2	4.5

* Cavities fabricated from high-thermal-conductivity niobium
** Cornell cavity design
Source: H. Piel, Wuppertal

Since superconducting linacs are likely to become the approach of choice for producing cw electron beams for nuclear physics, it is appropriate to discuss the status of superconducting rf technology.

Cavity shape is an important factor for both cost and performance. Within the past few years, several improvements in this area have been developed. Spherical or elliptical cell shape has been shown to reduce multipacting. Couplers for fundamental power and for higher order mode suppression attach to the beam pipe to minimize field enhancement and multipacting. The number of individual resonant rf cells (half wavelength) in a cavity is limited to control HOMs.

Optimized designs call for five cells or fewer. Cavity design and HOM suppression are aided now by the availability of computer codes such as URMEL.[24]

The most common superconductor currently in use is niobium. Since only a very thin surface layer on the inside of the cavity is active in the formation of the accelerating field, the quality and cleanliness of that surface layer is of the utmost importance to cavity performance. In addition, the surface layer must be kept below the superconducting transition temperature; cooling must be adequate to remove the heat generated by rf dissipation in dust and defects.

Recent developments in niobium processing and cavity fabrication have resulted in real progress in these areas. Niobium suppliers have developed the capability to produce niobium sheet with high thermal conductivity. High thermal conductivity helps to stabilize the cavity against being driven normal by resistive heating at a defect. Titanium treatment or yttrification can be used to increase the thermal conductivity.[25] The use of clean rooms and clean manufacturing protocols prevents the introduction of dust or dirt on the active surface. Refined electron beam welding methods help achieve weld smoothness.

Another recent development is thermometric mapping[26] to locate hot spots caused by defects or dirt on the superconducting surface. A cavity can be tested and the factor limiting its gradient can be located and repaired.

Although gradients of 5 to 7 MV/m and Q's in excess of 10^9 are achieved routinely by industry today in prototype cavities, the real attraction of rf structures is their potential to achieve gradients above 20 MV/m with very low rf losses ($Q >\geq 10^{10}$) and high beam-current capacity. Single-cell cavities fabricated at Cornell and Wuppertal have achieved such high gradients (Table 3), which are far below the theoretical limit. The gradient limit is determined by the magnetic field at which the superconductor goes normal, and is in the range of 50 to 100 MV/m for the superconducting materials of interest.

Experimentation is underway with Nb_3Sn, niobium on copper, and other superconductors as cavity materials.[3] Nb_3Sn offers the potential for lower rf losses and operation at higher temperatures. Niobium on copper would have a very high bulk thermal conductivity, thus providing excellent thermal stabilization of submicroscopic defects and dust.

In summary, the capabilities of superconducting accelerator cavities have improved significantly over the past decade. Reasonable design parameters achievable with niobium cavities fabricated by industry today are a frequency between 350 MHz and 3000 MHz, an accelerating gradient of 5 to 7 MV/m, and a Q of 2×10^9 to 3×10^9, with disruptive higher order mode Q's damped to 10^4 or 10^5. For nuclear physics applications, frequencies in the upper end of the frequency range may be preferred, because the individual micropulses cannot be resolved by the detectors, even after the frequency is reduced by splitting the beam to two or three experimental areas.

Currently under construction are two recirculating, superconducting cw linacs: one at the University of Darmstadt (West Germany), and one at CEBAF in Newport News, Virginia. Saclay (France) is developing a design and proposal, and the Italian Nuclear Physics Laboratory in Frascati is considering doing so. The following descriptions summarize the Darmstadt, CEBAF, and Saclay designs.

Darmstadt. Under construction at the Institut fur Kernphysik, Technische Hochschule, Darmstadt, West Germany, is a superconducting recirculating accelerator (Figure 10) based on 1-meter-long, 20-cell accelerating cavities operating at 3-GHz frequency.[27] The design gradient is 5 MV/m and the design Q is 3×10^9 at the operating temperature of 2.0 K.

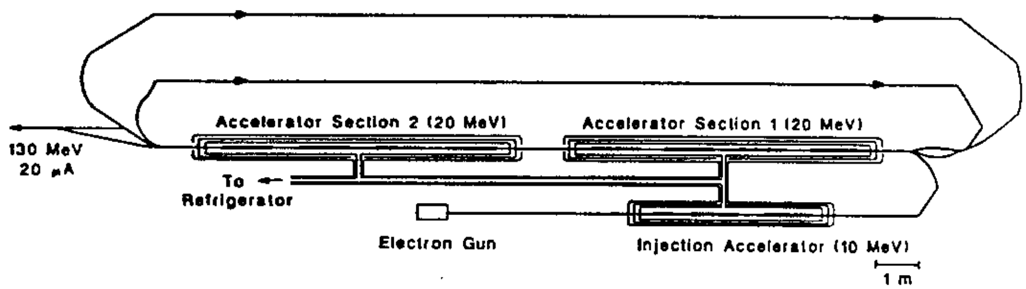

Figure 10. Darmstadt recirculating superconducting linac.

The Darmstadt electron beam is produced by a 350-keV gun and injected into one short (5-cell) and two 20-cell superconducting cavities to reach its 10 MeV injection energy. Subsequently the beam attains 130 MeV in three passes through two 20-MeV accelerating sections of four cavities apiece. The R&D work leading to the cavity design has been done in collaboration with the University of Wuppertal, which is also involved in the construction effort. The electron gun and cryogenic system are operating, and a 1.5-MeV beam has been produced using the first (short) injector cavity. Physics experiments are to begin shortly using the low-energy beam, and will continue as the machine is completed and commissioned.[28]

CEBAF. The Continuous Electron Beam Accelerator Facility (CEBAF)[29] in Newport News, Virginia, is planned as a state-of-the-art cw electron accelerator, producing a 4-GeV, 100%-duty-factor, 200-μA beam of 2×10^{-4} energy resolution. CEBAF's scientific objective is to study the structure of the nuclear many-body system, its quark substructure, and the strong and electroweak interactions prominent in the nucleus. The beam energy was specified by the U.S. nuclear physics community to access the confinement regime.

Acceleration is to take place in two antiparallel linac segments (Figure 11), with recirculation beam lines for four orbits. CEBAF's niobium accelerating cavities were developed by Cornell University's Newman Laboratory (Figure 12). They operate at 1.5 GHz and have five cells. The design specifications are a Q_0 of 2.4×10^9 at a gradient of 5 MV/m and a temperature of 2.0 K. In total, the two linac segments contain 400 cavities providing 1 GeV of acceleration.

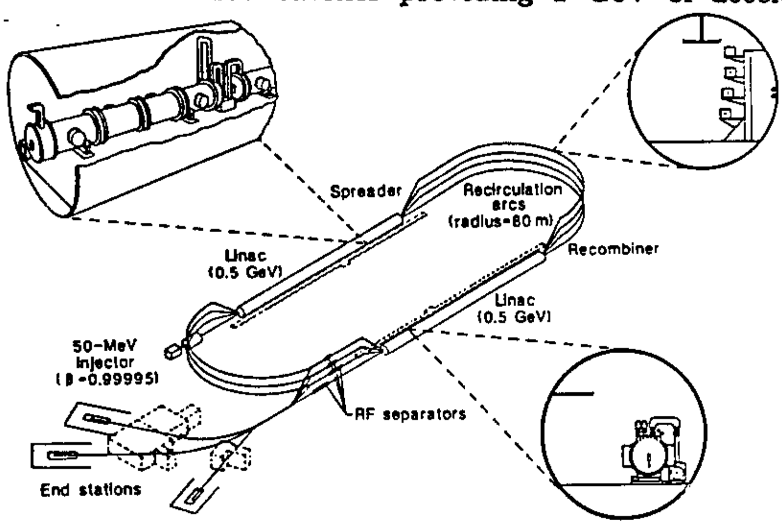

Figure 11. CEBAF recirculating superconducting linac.

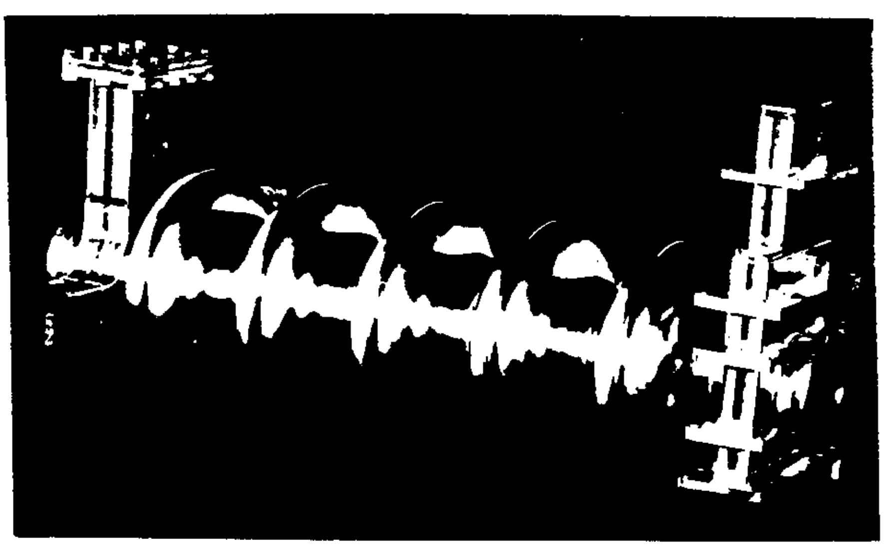

Figure 12. CEBAF-Cornell five-cell niobium cavity (length = 66 cm).

In addition, there are 18 superconducting cavities in the injector, which produces a nominal 50-MeV beam. During 1986, CEBAF and Cornell worked with industry to qualify vendors to produce these cavities. To date, six prototypes, all exceeding the specifications, have been delivered and tested.

A central helium liquefier supplies liquid helium at 2.0 K to insulated cryomodules, each containing eight cavities. The extraction system directs three simultaneous beams at optionally different energies to three experimental areas.

CEBAF has been approved and funded through the U.S. Department of Energy. Construction is scheduled to begin in January 1987 and to be completed in 1992.

Saclay. In the summer of 1986 plans were advanced to replace the existing, pulsed room-temperature linac--Accelerateur Lineare de Saclay (ALS)--at Saclay, France, with a recirculating, superconducting linac.[50] Figure 13 shows the stages in the proposed evolution of ALS Supra. By 1992 a 200-meter (70-meter active length) superconducting linac, built parallel to the existing 1%-duty-factor device, would produce a 500-700 MeV beam at 100% duty factor and 100 μA. Recirculation arcs would then be installed, the ALS tunnel would be used for antiparallel transport of the beam (without further acceleration), and by 1993, three-pass, 1.5-2 GeV operation of the single superconducting linac would be possible. In later upgrades, Saclay would install a second SC linac, a new injector, additional recirculation beam lines for a final energy as high as 6 GeV, and possibly some new experimental areas.

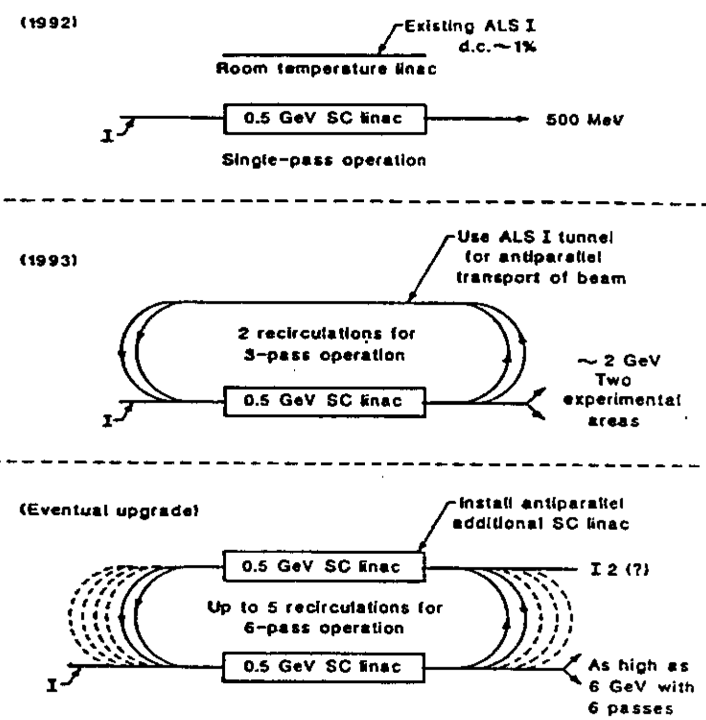

Figure 13. Possible evolution of ALS Supra.

ALS Supra is now being designed, and a cavity development program is underway, involving formal collaboration with CERN. Saclay proposes to develop four- or five-cell 1500-MHz cavities with coaxial couplers for fundamental power and for damping higher order modes. The design gradient is 7 MV/m.

In June 1986, the French nuclear physics community endorsed ALS Supra as their highest priority project.[81]

CONCLUSIONS

While the decisions on funding and construction have not been made for many of these new electron accelerators, the numerous proposals certainly presage exciting new opportunities for electromagnetic nuclear physics. It seems clear that the capabilities available globally to the experimentalist are shifting toward continuous beams, and to higher energies, while maintaining excellent energy resolution.

With the advent of superconducting rf technology as a practical means of providing high-quality cw beams, and its first major application in accelerators for nuclear physics, our field is assuming a leadership role for developing and testing accelerator technologies that have broad application. In this development, nuclear physics has the attention of the high-energy-physics and free-electron-laser communities, as well as industry. It is apparent that superconducting rf technology, conceived in the 1960s, has begun in the 1980s to deliver on its promises, and has considerable room to increase in performance and decrease in cost in the years ahead.

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